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**CHROMIUM DIOXIDE (CrO_2) AND COMPOSITES OF CHROMIUM DIOXIDE AND
OTHER OXIDES OF CHROMIUM SUCH AS $\text{CrO}_2/\text{Cr}_2\text{O}_3$ AND $\text{CrO}_2/\text{Cr}_2\text{O}_5$) AND
PROCESS FOR MANUFACTURING THE SAME**

BACKGROUND OF THE INVENTION

Field of the invention

[0002] The present invention relates to half metallic ferromagnetic chromium dioxide (CrO_2) in substantially pure form. The present invention further relates to composites of chromium dioxide and other oxides of chromium namely, $\text{CrO}_2 / \text{Cr}_2\text{O}_3$ and $\text{CrO}_2 / \text{Cr}_2\text{O}_5$. The present invention further relates to a process for manufacturing said substantially pure chromium dioxide and composites of chromium dioxide and other oxides. Chromium dioxide is a well known material used in magnetic recording applications. Apart from this, CrO_2 and the composites of CrO_2 with other oxides of chromium have wide application as a magnetoresistive and spintronic material.

Related Art of the Invention

[0003] **Pure CrO_2 :** Chromium dioxide (CrO_2) is a metallic, room temperature ferromagnet with Curie temperature (T_c) around 393 K. It has been widely used as a particulate media in magnetic recording applications since long. B.L Chamberland has reviewed in 1977 "The chemical and physical properties of CrO_2 and tetravalent chromium oxide derivatives" in *CRC Critical Rev. in Solid State and Mater. Sci.* 7, 1 (1977).

[0004] CrO_2 is also well known to be a half metallic ferromagnet. Half metallic ferromagnets are defined as ferromagnets in which conduction electrons are fully spin polarized at low temperatures where spin disorder is minimum (see "New class of materials : half metallic ferromagnets" R.A. Groot et.al, *Phy. Rev.Lett* 50 ,2024, 1983). It is desirable to maintain the spin polarization near room temperatures so that devices based on spin polarised current could be realized. The phenomenon of

spin polarized conduction has given rise to an upcoming field of spintronics wherein devices are based on spin polarized current. In 2001, Ji et.al, have observed, through Andreev reflection measurements, the maximum spin polarization close to 100% in CrO_2 , vis a vis other materials showing half metallicity. See "Determination of the spin polarization of half metallic CrO_2 by point contact Andreev reflection", *Phy. Rev. Lett.*, Y. ji et.al., **86**, 5585, 2001.

[0005] Polycrystalline CrO_2 is now well established to be a magnetoresistive and spintronic material. Here the magnetoresistance (MR) is defined as $\Delta R/R_0 = (R_H - R_0)/R_0$, where R_0 and R_H are the electrical resistance in zero field and in external magnetic field (H), respectively. Materials displaying negative MR greater than a few percent are used in various devices. Related prior art can be seen in US Patent 5,856,008.

[0006] Interestingly, CrO_2 is known to show the metallic conductivity in single crystals and epitaxially grown thin films. However, activated behavior is seen in polycrystalline CrO_2 that is believed to be arising from hopping/tunneling of the charge carrier across grain boundaries in polycrystals. This mechanism of 'spin polarized tunneling' of charge carriers across the grain boundaries which exist in polycrystalline samples were first proposed by Hwang et. al in their paper entitled " Spin polarized intergrain tunneling in $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$, *Phys. Rev.Lett.* 77, 2041 (1996). JMD Coey et. al, have related this mechanism of conduction to the origin of large magnetoresistance exhibited by polycrystalline CrO_2 in their paper entitled "Magnetoresistance of Chromium dioxide powder compacts, *Phy. Rev. Lett.* 80, 3815, 1998". One area in which half metallic ferromagnets have tremendous device application is Magnetic Tunnel Junctions. (Warren E Picket and Jagdeesh S Moodera, "Half-metallic Magnets"

Physics Today, May 2001). The half-metallic ferromagnets, as a magnetoresistive material have been employed in various magneto-electronic applications.

[0007] The utility of above-mentioned devices is significant when substantial MR is found near room temperatures. In case of polycrystalline CrO_2 , it is found that MR is maximum at lowest temperatures of the order of 5K and is known to decrease rapidly with increasing temperatures. For instance Coey et.al have reported MR of the order of 0.1% near room temperature in their paper entitled "Magnetoresistance of Chromium dioxide powder compacts, *Phy. Rev. Lett.* 80, 3815, 1998". There are several factors that may cause the loss of spin polarization. The presence of even a small amount of impurity phase not only affects the ferromagnetic properties but also interferes with the phenomenon of half metallicity/spin polarization severely. This results in the loss of spin polarization and thus brings down the efficiency of the concerned device, based on spin-polarized current.

[0008] Since CrO_2 is a material of industrial importance, there have been a large number of patents and papers on various preparation methods and intricacies involved for preparing CrO_2 . The related prior art is presented in Table 1. There are three important factors related to synthesis of CrO_2 (i) Taking CrO_3 as starting material, CrO_2 is not known to form in ambient pressure. (ii) Pressure temperature phase diagram is highly interlinked resulting in mixed phase compounds. (iii) It is known that once formed, sintering of CrO_2 is difficult since it is a metastable phase and easily converts to Cr_2O_3 even at modest temperatures of 200°C . (See L. Ranno, A. Barry and J.M.D. Coey, *J. Appl. Phys.*, 81, 5774 (1997)). This is an important issue related with the fabrication and reproducibility factor of devices based on CrO_2 .

[0009] Table 1.

US Patent	Starting Material	Temp. Pressure	Product	Remarks
2923685 (1960)	CrO ₃ , H ₂ O, Na ₂ SO ₄	450°C, 1000 Atm	CrO ₂	*
3423320 (1969)	KCr ₃ O ₈ , H ₂ O,	2600 Atm	CrO ₂	needle like FM
3449073 (1969)	CrO ₃ , Cr ₂ O ₃ , Na ₂ Cr ₂ O ₇	850 Atm	CrO ₂	fine grain particles
4428852 (1984)	preheated hydrated Chromium oxide	elevated pressure/ continuous process	CrO ₂	*
3117093 (1964)	Cr _x O _y 2y/x is 4 – 5.5	50 – 3000 Atm	CrO ₂	*
3493338 (1970)	CrO ₃ , NO, O ₂	225, 325 °C no pressure	CrO ₂ 94%+ CrO ₃ , 5%	*
5856008 (1999)	CrO ₃	520 °C 35000 bar	CrO ₂ CrO ₂ coated with Cr ₂ O ₃	* **

* Relevant to production of CrO₂; * * relevant to production of CrO₂ / Cr₂O₃ Composite.

[00010] Table 1 shows that

- (a) CrO₃ (chromium VI oxide) has been used as a starting material. CrO₂ can be prepared by thermal decomposition of CrO₃ and mixed chromium oxides.
- (b) There exist a very narrow window of temperature and pressure in which many other oxides of chromium stabilize, including CrO₂, and the phase boundary between these oxides is very fuzzy. Consequently a little variation in preparation condition results in mixed phase or impure compounds Chamberland has discussed this aspect by showing it in Figs.1 and 2 on page 3 of his review (*ibid.*).
- (c) The difficulties of accurately measuring and controlling pressure at elevated temperatures, along with the fact that it requires expensive high-pressure assemblies leading to high production cost are the main drawbacks of above-mentioned preparative methods. It is desirable to have a preparative method, which does not need pressure as controlling parameter.

(d) The last three US patents in the above table form relevant prior art to the present invention and will be discussed after describing the present invention in detail.

[00011] A ferromagnetic sample is characterized by its saturation magnetization M_s at 0 K and Curie temperature T_c . The theoretical value for saturation magnetization for CrO_2 is about 135 emu/gm. The best-reported value for the saturation magnetization for polycrystalline samples range from 75 -87 emu/gm as reported in earlier patents (Table 2). The single crystals have shown value of the order of 108 emu/gm. The best values of M_s for polycrystalline CrO_2 supplied by DuPont is from 87-110 emu/g as given in " Spin phonon coupling in rod shaped half metallic CrO_2 ultra fine particles: a magnetic Raman scattering study, T Yu et al., J. Phys. Condens. Matter **15**, L213, 2003 and "Junction like magnetoresistance of intergranular tunneling in field aligned chromium dioxide powders", Jianbiai Dai and Jinke Tang, Phy. Rev. B, 63, 054434 (2001).

[00012] It is thus noted that for bulk polycrystalline CrO_2 , the value of saturation magnetization more than 110 emu/g has not been reported in earlier.

[00013] Since the saturation magnetization value (M_s) is an important criterion for a pure ferromagnetic material, and is a test for comparing various processes, some M_s values from literature for CrO_2 are given in Table 2.

[00014] **Table 2: Saturation Magnetization Values for CrO_2 as reported in literature**

Reference	Saturation Magnetization (M_s) (emu/gm)
Theoretical Value of M_s	~135*

US Patent 4747974 (polycrystalline)	75-78
US Patent 3493338 (polycrystal)	24-84 (including modifier)
US Patent 3486851 (polycrystal)	78-87
US Patent 3451771 (polycrystal)	21-35
US Patent 2923683 (polycrystal)	38-66 (with modifier)
Poly crystal Chamberland (1977)	73-75
Single crystal (Chamberland 1977)	108
Polycrystals supplied by DuPont	~100-110 emu/g

**Note: For calculating the theoretical value of M_s , density of the CrO_2 is taken as 4.8 g/cm^3 . However the density calculated from X-Ray measurements is found to be 4.89 g/cm^3 whereas observed density is of the order of 4.8 g/cm^3 . This point is discussed in the review article on CrO_2 by Chamberland, Page 10*

[00015] **Composites of CrO_2 and Cr_2O_3 :** An important aspect related with $\text{CrO}_2/\text{Cr}_2\text{O}_3$ composites is that it is also a magnetoresistive material. The most important aspect of composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) is that they show an enhancement of magnetoresistance ratio over pure polycrystalline chromium dioxide at low temperatures. It is known that the percentage magnetoresistance is increased when insulating Cr_2O_3 is added to metallic CrO_2 . However, composites having high magnetoresistance near room temperature have not been reported which is more significant from the device application point of view. Moreover, the known composites are in the cold pressed form due to the reason that CrO_2 once formed, is known to be a metastable phase which degrades at temperatures as moderate as 200°C . Due to this reason neither pure CrO_2 nor its composites can be sintered to make hard pellets for practical usage. Hard

pellets are made by putting chemical binder etc. This difficulty exists for bulk transport measurements for which sintered forms of the composite is desirable.

[00016] Composites prepared by known methods lack homogeneity as well as reproducibility factor which is important for all practical purposes of using composites as a magnetoresistive material in device applications. Generally a $\text{CrO}_2/\text{Cr}_2\text{O}_3$ composite may be obtained by (i) annealing pure CrO_2 in oxygen at elevated temperatures preferable in the range 350 to 500 C (US Patent 5,856,008) (ii) mixing of pure CrO_2 in pure Cr_2O_3 to obtain a composite in desirable ratio (See JMD Coey et al Phy. Rev. Lett. 80, 3815, 1998). Both annealing process and mixing process have their own disadvantage. For instance as taught in US 5,856,008, annealing of CrO_2 above a certain temperature results in Cr_2O_3 layer of thickness that inhibit intergrain tunneling and therefore reduce the magnetoresistance. This puts the upper limit on the mass fraction of Cr_2O_3 in CrO_2 . Since it is known that the % MR can be tuned depending on the mass fraction of Cr_2O_3 in CrO_2 , it is desirable to have a process through which mass fraction of Cr_2O_3 can be easily controlled. Similarly a composite obtained by mixing CrO_2 and Cr_2O_3 in desired ratio cannot be obtained in sintered form, besides the final MR value depends on the grain size and porosity of the sample, which may vary with grinding time, and pressure at which the samples were cold pressed. Thus known methods do not allow systematic control of homogeneous proportion of Cr_2O_3 in a composite. Additionally, in the known methods, varying oxygen pressure controls the proportion of Cr_2O_3 and a slight variation in experimental condition may adversely affect the reproducibility of physical properties.

[00017] **Composites of CrO_2 and Cr_2O_5 :** Cr_2O_5 is another oxide of Cr which is insulating. The product Cr_2O_5 is a well known compound

and is well documented in literature. However the composites of CrO_2 with Cr_2O_3 have not been studied in terms of % MR.

SUMMARY OF THE INVENTION

[00018] Therefore the object of the present invention is to provide half-metallic ferromagnet, substantially pure polycrystalline chromium dioxide (CrO_2) having saturation magnetization values close to the theoretical value.

[00019] Another object of the present invention is to provide pure polycrystalline chromium dioxide CrO_2 , which can be obtained in cold pressed as well as sintered forms and which has enhanced magnetoresistance near room temperature.

[00020] Yet further object of the present invention is to provide composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) which can be cold pressed as well as sintered.

[00021] Another object of the present invention is to provide composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) which has enhanced magnetoresistance at low temperature as well as near room temperature.

[00022] A further object of the present invention is to provide composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) which is substantially homogenous.

[00023] Yet another object of the present invention is to provide composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) which can be obtained in any desired ratio of the constituent compounds.

[00024] Yet another object of the present invention is to provide a process for the manufacture of half metallic ferromagnet, substantially pure chromium dioxide (CrO_2), or composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) which does not involve maintaining of high pressure as a control parameter during the process of synthesis.

[00025] A further object of the present invention is to provide a process for the manufacture of half metallic ferromagnet, substantially pure chromium dioxide (CrO_2), or composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) which is simple and cost effective.

[00026] A further object of the present invention is to obtain composites of CrO_2 and other oxide of chromium such as Cr_2O_5 and study MR in this class of compounds.

[00027] A further object of the present invention is to provide a process of manufacture of polycrystalline samples of (a) substantially pure CrO_2 (b) composites of $\text{CrO}_2/\text{Cr}_2\text{O}_3$ (c) composites of $\text{CrO}_2/\text{Cr}_2\text{O}_5$ wherein a single tunable experimental parameter is needed to obtain (a), (b) and (c).

[00028] According to the present invention there is provided substantially pure chromium dioxide (CrO_2) having saturation magnetization of above 110 emu/gm and preferably at least 115 emu/gm.

[00029] The present invention also provides composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) having negative magnetoresistance of at least 0.5% near room temperature at 2 Tesla.

[00030] The present invention also provides composites of chromium dioxide and Cr_2O_5 ($\text{CrO}_2/\text{Cr}_2\text{O}_5$) having enhanced negative magnetoresistance of at least 0.5% near room temperature at 2 Tesla.

[00031] The present invention further provides a process for manufacture of half metallic ferromagnet, substantially pure chromium dioxide (CrO_2), or composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) or composites of chromium dioxide and Cr_2O_5 ($\text{CrO}_2/\text{Cr}_2\text{O}_5$) comprising heating an intermediate oxide of chromium to a temperature of between 350 and 500°C for a period of between 1-5 hours whereby substantially pure chromium dioxide (CrO_2), or composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) or composites of chromium dioxide and Cr_2O_5 ($\text{CrO}_2/\text{Cr}_2\text{O}_5$) are formed.

Detailed description of the invention

[00032] Half metallic ferromagnet, substantially pure chromium dioxide (CrO_2) according to the present invention exhibits saturation magnetization (M_s) of at least 115 emu/gm. Preferably the M_s value is atleast 120 emu/gm and most preferably 135 emu/gm for cold pressed sample of CrO_2 and 126 emu/g for sintered pellets. As a consequence of such high purity of the sample, there is evidence of maintained spin polarization near room temperature and the chromium dioxide of the present invention exhibits negative magnetoresistance of atleast 0.5% near room temperature at 2 Tesla, preferably 2% and most preferably 5 % MR at room temperature at 2 Tesla for sintered pellet of pure CrO_2 .

[00033] Composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) according to the present invention have enhanced negative magnetoresistance of atleast 0.5% near room temperature at 2 Tesla. More preferably, the composites have negative

magnetoresistance of at least 2%, more preferably 5% near room temperature at 2 Tesla. Most preferably the negative magnetoresistance is 32% at room temperature and 2 Tesla in a sample of $\text{CrO}_2/\text{Cr}_2\text{O}_3$ composite. This composite contained nearly 40% Cr_2O_3 . Composites of the present invention also show saturation magnetization of about 75 emu/gm at 5K for a 40% molar Cr_2O_3 composite and 103 emu/gm at 5K for a 25% molar Cr_2O_3 composite. Composites of the present invention can be obtained in sintered form facilitating bulk transport measurements. Moreover, the composites are obtainable in any ratio of the constituent compounds and are homogenous. The composites also show substantial reproducibility and are therefore appropriate for use as magnetoresistive materials in device applications.

[00034] Composites of chromium dioxide and Cr_2O_5 ($\text{CrO}_2/\text{Cr}_2\text{O}_5$) according to the present invention have enhanced negative magnetoresistance of atleast 0.5% near room temperature at 2 Tesla. More preferably, the composites have negative magnetoresistance of at least 2%, more preferably 5% near room temperature at 2 Tesla. Most preferably the negative magnetoresistance is 22% at room temperature and 2 Tesla. Composites of the present invention also show saturation magnetization of around 60 emu/gm and preferably around 80 emu/gm at 5K where the fraction of CrO_2 is systematically varied. Composites of the present invention can be obtained in sintered form facilitating bulk transport measurements. Moreover, the composites are obtainable in any ratio of the constituent compounds and are homogenous. The composites also show substantial reproducibility and are therefore appropriate for use as magnetoresistive materials in device applications.

[00035] The process of the present invention comprises extraordinary simple steps for the manufacture of either half-

metallic ferromagnetic chromium dioxide (CrO_2), or composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) or composites of chromium dioxide and Cr_2O_5 ($\text{CrO}_2/\text{Cr}_2\text{O}_5$) with following merits - (a) It does not require pressure as a control parameter (b) unlike prior art, no chemical modifier has been used to bring down the operating pressure during the synthesis. This is significant as addition of modifier may depolarize the spin. (c) For the first time, fairly hard, sintered pellets of CrO_2 , $\text{CrO}_2/\text{Cr}_2\text{O}_3$ as well as $\text{CrO}_2/\text{Cr}_2\text{O}_5$ composites have been prepared. Most importantly, no chemical binder has been used to obtain sintered pellets. Earlier work reports either cold pressed pellets or the pellets hardened by using a chemical binder, which may depolarize the spin. (d) The saturation magnetization is found to be at least 120 emu/gm and particularly around 135 emu/g for the cold pressed and 126 emu/g for the sintered pellets of CrO_2 . To the best of inventor's knowledge, this is the highest quoted value of M_s compared to other samples reported in literature for bulk CrO_2 . (e) The composites of $\text{CrO}_2/\text{Cr}_2\text{O}_3$ and $\text{CrO}_2/\text{Cr}_2\text{O}_5$ have shown significant negative MR near room temperatures as well as at low temperatures.

[00036] The process of present invention comprises the following reactions.

[00037] A: An intermediate oxide of chromium $\rightarrow \text{CrO}_2$ or composite $\text{CrO}_2 / \text{Cr}_2\text{O}_3$ or $\text{CrO}_2/\text{Cr}_2\text{O}_5$ by heating at 350-500 °C. This intermediate oxide is primarily Cr_8O_{21} with some traces of Cr_2O_5 as seen in X Ray Diffraction patterns. This intermediate oxide would be referred to as precursor subsequently.

[00038] According to the above process, when temperature is maintained between 380°C and 400°C CrO_2 is formed as the product (Step A1) and when the temperature is between 400°C to 500°C it

gives CrO_2 / Cr_2O_3 composites (Step A2). When the temperature is between 350°C to 380°C then $\text{CrO}_2/\text{Cr}_2\text{O}_5$ composites are formed (Step A3). The exact temperature for the formation of compound at step A1 or step A2 or step A3 depends on the quality of the precursor. For a given precursor, if temperature range of step A1 is shifted by a few degrees then there is a systematic shift in the temperature ranges of step A2 or step A3.

[00039] In step A, it is preferred to maintain the temperature of intermediate oxide in the specified range for 2-3 hours. To convert precursor to substantially pure CrO_2 according to step A1 it is preferred to maintain the temperature range between 390 - 400°C and to convert precursor to the said composite of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) according to step A2 the temperature range should be preferably maintained between 400 - 450°C . To convert precursor to the said composites of CrO_2 and Cr_2O_5 ($\text{CrO}_2/\text{Cr}_2\text{O}_5$) according to step A3, the temperature range should be between 350 to 390°C .

[00040] According to a preferred aspect intermediate oxide is prepared from CrO_3 by heating the CrO_3 and maintaining the temperature from 220 - 330°C for 6 to 14 hours, preferably for 8-12 hours, with or without oxygen flow. It is further preferred to maintain a temperature in the range of 230 - 280°C and oxygen flow.

[00041] CrO_3 is taken in an inert container and heated slowly to raise the temperature to about 250°C and thereafter maintained in the temperature range of 250°C - 270°C for about 8-12 hours in dry oxygen/air at about atmospheric pressure, till it is converted to said precursor which is a specific intermediate oxide of Chromium, primarily Cr_8O_{21} as characterized by X ray diffraction. Thereafter precursor is cooled to room temperature at the same rate as was used for raising the temperature initially.

[00042] The precursor so formed is crushed in any inert vessel to form a powder and then the powder is sealed in a glass tube of inert material. The powder can also be pelletized and sintered before sealing it in the inert tube. Thereafter the tube is placed in a preheated furnace maintained at a temperature in the range of about 350-500°C for about 2-3 hours till it is converted to said half-metallic ferromagnet viz. said substantially pure chromium dioxide CrO_2 when at 390 - 400°C or a composite of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) when at 400 - 500°C, or a composite of CrO_2 and Cr_2O_5 when at 350-390 °C as characterized by XRD.

[00043] The sealed tube is then opened after cooling it to ambient temperature and the contents are stored in any dry container.

[00044] After lot of experimentation we have found that the stoichiometry of the final product at a certain temperature depends on the quality of precursor. It is found that stoichiometric CrO_2 can be prepared even if oxygen flow was not maintained while making the precursor though it is preferable to maintain the oxygen flow. A slight variation in experimental conditions leads to the formation of undesirable impurity in the precursor, which may adversely affect the quality of CrO_2 . Further, in case of composites of $\text{CrO}_2/\text{Cr}_2\text{O}_3$, the ratio of mass fraction of Cr_2O_3 in CrO_2 can be systematically varied by varying the temperature in step A2 for making a composite in desired ratio. Same holds true for the $\text{CrO}_2/\text{Cr}_2\text{O}_5$ composites.

[00045] US patent 3,493,338 teaches a one step reaction: $\text{CrO}_3 \rightarrow \text{CrO}_2$. There is no isolation of the intermediate product. Heat treatment cycle is as follows: RT \rightarrow 175 °C in 10 min. \rightarrow 225 °C in

1 hour \rightarrow 325 °C in 20 min. and maintained at 325 for 2 hrs. All the while there is gas (- a mixture of 3.5 % NO and O₂) flow at normal atmospheric pressure is run over the boat carrying CrO₃ at about 200 cc /min. The M_s value of the CrO₂ obtained is ~ 84 emu/g, whereas that in the present process product is ~ 132 emu/g.

[00046] The US patent 3,117,093 teaches two step process, the second step starting with Cr_xO_y with average chromium valance ratio (2y/x) of 4.2 - 4.3 This is mixed with water and other modifiers such as antimony sesquioxide inside a platinum tube and reaction carried out under a pressure of 50 - 3000 Atm. There are, however 3 examples (No.14, 15 and 16) in this patent, which describe the process without any modifier. The first step starts with chromic nitrate monohydrate; it is heated at 330 °C for 2 hours to obtain an intermediate chromium oxide Cr_xO_y not a well-defined compound as said above. In these three examples the reaction Cr_xO_y \rightarrow CrO₂ was carried out at 400 °C for 1 to 2 hours. This starting material Cr_xO_y was either moist 3 - 9 % moisture or taken water for milling before heat treatment. Though in these examples there is no mention about pressure, the reaction has been claimed to be done at from 50 - 3000 atmosphere pressure. It will be clearly seen that the Step A of the present invention is different from this prior art. The starting material in step B of the present invention is different from this prior art. Step B in the present invention is in dry state that in these examples without modifier in the US patent 3,117,093 is in the moist state. The temperature of the reaction at step B is 400°C at 750 atmospheres and 17% water, in the US patent 3,117,093. Conditions are therefore different in the present invention for production of CrO₂.

[00047] Thus the process of present invention is different from this prior art process.

[00048] In the process taught in US patent 5,856,008, the reaction $\text{CrO}_3 \rightarrow \text{CrO}_2$ is carried out in a gold capsule at 35 kbar pressure at 520 °C for 2 hours in a piston cylinder type high pressure furnace; on cooling to room temperature the pressure is removed.

[00049] Thus this is a one step reaction different from the process of present invention. The CrO_2 thus obtained is annealed for 30 minutes in air at 380 °C, and another sample at 420 °C. And it is believed that in this process CrO_2 gets a thick surface coating of Cr_2O_3 which may inhibit electrical conduction.

[00050] In the process of present invention, $\text{CrO}_3 \rightarrow$ intermediate oxide (precursor) $\rightarrow \text{CrO}_2$ or composite $\text{CrO}_2 / \text{Cr}_2\text{O}_3$ or composite $\text{CrO}_2 / \text{Cr}_2\text{O}_5$ by heating precursor in sealed glass tube at 350 - 450 °C while using preheated furnace for any given temperature, and is clearly different from US patent 5,856,008. The process of present invention for manufacture of composites is simpler and does not need pressure as a control parameter. Besides in present invention, it is possible to obtain sintered pellets of the composite in which mass fraction of Cr_2O_3 or Cr_2O_5 can be precisely controlled. Depending on the grinding time before pelletization of the intermediate oxide, we speculate that it is possible to vary the grain size of metallic CrO_2 in insulating Cr_2O_3 (the $\text{CrO}_2/\text{Cr}_2\text{O}_3$ composites) or in insulating Cr_2O_5 (the $\text{CrO}_2/\text{Cr}_2\text{O}_5$ composites).

EXAMPLES

[00051] The invention will now be illustrated with the help of examples. The examples are by way of illustration only and in no way restrict the scope of the invention.

Equipment Used:

[00052] The equipment used in these examples is a tubular furnace (Carbolite model CTF12/65 furnace). The furnace has a temperature range up to 1200°C and has the arrangement for flow of inert or oxygen flow.

[00053] Inert containers used for reaction are chosen from quartz, Pyrex glassware.

[00054] **Chemicals used:**

CrO₃ granules with 99.9% purity were obtained from Aldrich Chemical Company, USA. Alternatively, CrO₃ flakes can also be used as a starting material.

[00055] **Analytical Facilities used:**

Siemens Diffractometer (Model D-500): for powder X-ray diffraction measurements (XRD).

[00056] Wave Dispersive Electron Probe Microanalyser (CAMECA Model EPMA SX-100): for scanning electron microscopy (SEM).

[00057] Vibrating Sample Magnetometer (Oxford MagLab VSM) and SQUID magnetometer (Quantum Design MPMS-XL7): for magnetization measurements.

[00058] Physical Properties Measurement System (Quantum Design PPMS-9) and home made Magnetoresistance set-up: for magnetoresistance measurements.

[00059] Program DBWS 486 was used for Rietveld profile refinement of XRD data. (R.A.Young, A. Sakthivel, T.S. Moss and C.O. Paovasantos, User's Guide to program DBWS-9411 (Georgia institute of technology, Atlanta 1994).)

[00060] Standard JCPDS data were used to identify the Bragg Peaks in XRD

[00061] Description of Figures in the accompanying drawings:

Fig.1 (a) - (e): X-Ray diffraction pattern (2θ vs. Intensity) for the product of Examples I, II, III, IV, V respectively. Solid lines are Rietveld X-ray profile refinement fit to the experimental data. The fitting is done using Rietveld profile refinement program. These samples are pure and Stoichiometric CrO_2 in which no detectable impurity phases were found in X-ray diffraction measurements.

Fig.1 (f) - (g): X-Ray diffraction pattern (2θ vs. Intensity) for the product of Examples VI, VII respectively; Solid lines are Rietveld X-ray profile refinement fit to the experimental data. These samples are $\text{CrO}_2/\text{Cr}_2\text{O}_3$ composites. The X-ray diffraction measurements shown in Fig 1(f) and 1(g) show the distinct Bragg peaks corresponding to CrO_2 and Cr_2O_3 phase.

Fig.1 (h) - (i): X-Ray diffraction pattern (2θ vs. Intensity) for the product of Examples VIII, IX respectively; These samples are $\text{CrO}_2/\text{Cr}_2\text{O}_5$ composites. The X-ray diffraction measurements shown in Fig 1(h) and Fig1(i) show the distinct Bragg peaks corresponding to CrO_2 and Cr_2O_5 phase.

Fig. 2: Scanning Electron Micrograph of the product of Example IV. The Long Needle shaped structures show the regular shape of CrO_2 particles.

Fig. 3(a): Magnetization (M) as a function of magnetic field (H) for the products of Examples I, III, IV, V at 5 K. The saturation magnetization (M_s) is found to be 132 and 135 emu/g for

the cold pressed CrO_2 (example I & example III) and 126 and 127 emu/g for the sintered CrO_2 (example IV and example V).

Fig.3(b): Magnetization (M) as a function of magnetic field (H) for the products of Examples VI and Example VII which are $\text{CrO}_2/\text{Cr}_2\text{O}_3$ composites, at 5 K. The saturation magnetization (M_s) is found to be 75 emu/g for the product of example VI which is a sintered $\text{CrO}_2/\text{Cr}_2\text{O}_3$ composite, and it is about 103 emu/g for the product of example VII which is a cold pressed (unsintered) composite.

Fig.3(c): Magnetization (M) as a function of magnetic field (H) for the products of Examples VIII and Example IX which are $\text{CrO}_2/\text{Cr}_2\text{O}_5$ composites, at 5 K. The saturation magnetization (M_s) is found to be 60 emu/g for the product of example VIII, and it is about 80 emu/g for the product of example IX. Both composites are sintered pellets.

Fig. 4(a). % Magnetoresistance (MR) as a function of temperature for sample in example IV which is a pure and sintered CrO_2 . Here the Magnetic Field H is parallel to the direction of current during the measurement. negative MR near room temperature is about 5% at 2 Tesla as opposed to 0.1 % quoted by JMD Coey et al for polycrystalline CrO_2 .

Fig. 4(b). % Magnetoresistance (MR) as a function of temperature for sample in example V which is a sintered pellet of CrO_2 . Here the Magnetic Field H is perpendicular to the direction of current during the measurement using PPMS system. The negative MR room temperature is about 3 % at 2 Tesla.

Fig. 4(c). % Magnetoresistance (MR) as a function of temperature for sample in example VI which is a sintered composite

of $\text{CrO}_2/\text{Cr}_2\text{O}_3$. The mass fraction of Cr_2O_3 in this sample is determined to be about 40 % from Rietveld Profile refinement technique. The room temperature negative MR is about 32 % at 2 Tesla.

Fig. 4(d). % Magnetoresistance (MR) as a function of temperature for sample in example VII which is an unsintered composite of $\text{CrO}_2/\text{Cr}_2\text{O}_3$. The mass fraction of Cr_2O_3 in this composites is about 25 % as determined from the Rietveld profile refinement of X ray data. The room temperature negative MR is about 8 % at 2 Tesla.

Fig. 4(e). % Magnetoresistance (MR) as a function of temperature for sample in example VIII which is a sintered composite of $\text{CrO}_2/\text{Cr}_2\text{O}_5$. The negative MR at room temperature is about 22% at 2 Tesla.

Fig. 4(f). % Magnetoresistance (MR) as a function of temperature for sample in example IX which is a sintered composite of $\text{CrO}_2/\text{Cr}_2\text{O}_5$. The Mass fraction of Cr_2O_5 is less in this composites as compared to the composite of example VIII as evident from X ray and Magnetization measurements. The negative MR at room temperature is about 8% at 2 Tesla.

Example I:

[00062] Chromium trioxide (CrO_3) was taken in a Pyrex glass tube and it was heated slowly to raise the temperature to about 250°C , and thereafter the temperature was maintained at 250°C , for 10 hours under oxygen flow at about atmospheric pressure. The end product was a mixture of intermediate oxide Cr_8O_{21} with traces of other intermediate oxide Cr_2O_5 . This end product forms in a hard bar, which was crushed and powdered using agate mortar.

[00063] This powder of intermediate oxide (approx. 500 mg) obtained as above, was placed inside a Pyrex glass tube of 12 cm length and 1.5 cm diameter. The glass tube was sealed at atmospheric pressure and the ampoule was kept in a preheated tube furnace at 392°C for 2 hours. The sealed glass tube was taken out from the furnace at the same temperature and thereafter it is opened at ambient temperature.

[00064] X-ray diffraction, Rietveld refinement of powder XRD (R.A. Young et al Program DBWS-9411, 1994) was performed on this sample. The results are shown in Fig. 1(a). This product was therefore CrO₂ as evident from XRD pattern.

[00065] The powder was examined for the measurement of saturation magnetization on a SQUID magnetometer (Model MPMS-XL7 of Quantum Design, USA). At a temperature of 5K, this powder shows saturation magnetization (M_s) as large as 132 emu/gm, which is very close to the theoretically predicted value 135 emu/gm (see E. P. Wohlfarth, Ferromagnetic Materials Vol.2, 471, 1980) [See Fig.3a]. This proved that the CrO₂ product obtained at the end of Example I was a substantially pure material. For comparison of reported M_s values of different CrO₂, see Table 2. The product of Example I - has the substantially high M_s value and it is very close to the theoretical value.

Example II

[00066] The procedure of Example I was repeated, the only change being the precursor (1.5 g) was sealed inside a test tube of 1 cm diameter and 10 cm length. It was placed in the furnace at 392 °C for 2 hrs. The final product was stoichiometric CrO₂, and was identical with product of Example I in the above tests. The product of present invention is CrO₂ of polycrystalline type as

confirmed by X-ray diffraction measurements, where no impurity peaks are observed (Fig 1(b)).

Example III

[00067] The procedure of Example I was repeated, the change being the precursor (1.5 g) was sealed inside a test tube of 1 cm diameter and 10 cm length. It was placed in the furnace at 400 °C for 2 hrs. The final product is CrO₂ of polycrystalline type as confirmed by X-ray diffraction measurements, where no impurity peaks are observed (Fig 1(c)). The powder was examined through the measurement of saturation magnetization on SQUID magnetometer. At a temperature of 5K, this powder shows saturation magnetization (M_s) as large as 135 emu/g (see Fig.3(a)) It will be seen that this is the only compound -the product of example III which has the highest M_s value.

Example IV

[00068] The procedure of Example I was repeated, the only change being precursor (about 1 g) was ground for few hours and pelletized in the form of a pellet of about 1.2 cm diameter and 0.2 cm thickness. This pellet was sintered at 250°C for few hours in tubular furnace. It was cooled to room temperature and was then sealed in a glass ampoule at atmospheric pressure. This ampoule was kept in the oven at 392°C for 2 hrs. The final product was a fairly hard pellet of stoichiometric CrO₂.

[00069] The product of Example IV was examined at room temperature under Scanning Electron Microscope (SEM). The SEM analysis was done on electron probe microanalysis (EPMA) system (model SX-100 from M/s CAMAC, France). The SEM picture is shown in Fig. 2, where long needle shaped grain are seen.

[00070] The X-ray diffraction measurement was done as in Example I and results are shown in Fig. 1(d).

[00071] The product of Example IV was examined for the measurement of saturation magnetization (M_s) as in Example I. The results are shown in Fig. 3a. The saturation magnetization is of the order of 126 emu/gm for this sample at 5 K (Table 3).

[00072] Magnetoresistance measurements were conducted on this sample in the temperature range from 5 K to 300 K in the presence of magnetic fields of the order of 2 Tesla. The applied magnetic field H was parallel to the direction of the current i during the measurement ($H \parallel i$). Large negative MR defined as $(R_H - R_0)/R_0$ was obtained as shown in Fig 4a. Significant negative MR of the order of 5 % was obtained near room temperature as shown in Fig 4a.

Example V:

[00073] The procedure of example IV was repeated with the only change that that the precursor in the form of sintered pellet was kept in the preheated furnace at 400°C. The results of X-ray diffraction are shown in Fig. 1(e).

[00074] The product of Example V was examined through the measurement of saturation magnetization (M_s) as in Example I. The results are shown in Fig. 3a. The saturation magnetization is of the order of 127 emu/gm for this sample at 5 K (Table 1). We also find that by varying the time of sintering of the intermediate oxide after pelletizing, the hardness of the pellet can be varied as may be required for some specific application.

[00075] Magnetoresistance measurements were conducted on this sample in the temperature range from 5 K to 300 K in the presence of magnetic fields of the order of 2 T. Here the applied magnetic

field H was perpendicular to the direction of the current during the MR measurement ($H \perp i$) Large negative MR defined as $(R_H - R_0)/R_0$ was obtained as shown in Fig 4b. Significant negative MR of the order of 3 % was obtained near room temperature as shown in Fig 4b.

Example VI

[00076] The procedure of Example V was repeated, with the only change of precursor in the form of sintered pellet (1 g) was sealed in a glass tube which was kept in the oven maintained at temperature at around 420°C.

[00077] The X-ray diffraction examination was done as in Example VI and the results are shown in Fig. 1(f). The product formed was found to be a composite of $\text{CrO}_2/\text{Cr}_2\text{O}_3$ from XRD.

[00078] The fraction of insulating Cr_2O_3 was also determined to be 40% (molar).

[00079] The product of Example VI was examined for M_s value, as in Example I. (See Fig. 3b). The M_s value found to be 75 emu/gm at 5 K.

[00080] Magnetoresistance measurements were conducted on this sample in the temperature range from 5 K to 300 K in the presence of magnetic fields of the order of 2 T. ($H \perp i$) Large negative MR defined as $(R_H - R_0)/R_0$ was obtained as shown in Fig 4c. Significant negative MR of the order of 33 % was obtained near room temperature as shown in Fig 4c.

Example VII

[00081] The procedure of Example I was repeated, with the only change of precursor in the powder form (1 g) sealed in a

glass tube was kept in the tube furnace maintained at temperature at around 410°C. The X-ray diffraction examination was done as in Example I and the results are shown in Fig. 1(g). The product formed was found to be a composite of $\text{CrO}_2/\text{Cr}_2\text{O}_3$ from XRD.

[00082] The fraction of insulating Cr_2O_3 was also determined to be 25% (molar) from the Rietveld profile refinement of X-ray data.

[00083] The product of Example V was examined for M_s value, as in Example I. The M_s value found to be 103 emu/gm at 5 K as is shown in Fig 3b.

[00084] Magnetoresistance measurements were done on this sample in the temperature range 5K to 300 K in the magnetic fields of the order of 2T. Here the H was parallel to the direction of current i during the measurement. Results are shown in Fig 4d. A significant negative MR of 8% was obtained near room temperature for this sample.

Example VIII

[00085] The procedure of Example IV was repeated, with the only change of precursor in the form of sintered pellet (1.5 g) was sealed in a glass tube which was kept in the oven maintained at temperature at around 385°C.

[00086] The X-ray diffraction examination was done as in Example I and the results are shown in Fig. 1(h). The product formed was found to be a composite of $\text{CrO}_2/\text{Cr}_2\text{O}_5$ from XRD.

[00087] The product of Example VIII was examined for M_s value, as in Example I. (See Fig. 3c). The M_s value found to be around 60 emu/gm at 5 K.

[00088] Magnetoresistance measurements were conducted on this sample in the temperature range from 5 K to 300 K in the presence of magnetic fields of the order of 2 T (here $H \perp i$). Large negative MR defined as $(R_H - R_0)/R_0$ was obtained as shown in Fig 4e. Significant negative MR of the order of 22 % was obtained near room temperature as shown in Fig 4e.

Example IX

[00089] The procedure of Example IV was repeated, with the only change of precursor in the form of sintered pellet (1 g) was sealed in a glass tube which was kept in the oven maintained at temperature at around 390°C.

[00090] The X-ray diffraction examination was done as in Example I, and the results are shown in Fig. 1(i). The product formed was found to be a composite of $\text{CrO}_2/\text{Cr}_2\text{O}_5$ from XRD.

[00091] The product of Example IX was examined for M_s value, as in Example I. (See Fig. 3c). The M_s value found to be 80 emu/gm at 5 K.

[00092] Magnetoresistance measurements were conducted on this sample in the temperature range from 5 K to 300 K in the presence of magnetic fields of the order of 2 T (here $H \perp i$). Large negative MR defined as $(R_H - R_0)/R_0$ was obtained as shown in Fig 4f. Negative MR of the order of 8 % was obtained near room temperature as shown in Fig 4f.

[00093] The saturation magnetization (M_s) and magnetoresistance (MR) measurements conducted on products of example I to example IX are summarized in table 3 and table 4.

[00094] Table 3: M_s Values at 5K for polycrystalline samples of the present invention

Unsintered CrO_2 example I, III	132 to 135, emu/g
Sintered CrO_2 example IV, V	126, 127 emu/g
$\text{CrO}_2/\text{Cr}_2\text{O}_3$ Sintered Composite Example VI	75 emu/g
$\text{CrO}_2/\text{Cr}_2\text{O}_3$ Unsintered Composite Example VII	103 emu/g
$\text{CrO}_2/\text{Cr}_2\text{O}_5$ Sintered Composite Example VIII	60 emu/g
$\text{CrO}_2/\text{Cr}_2\text{O}_5$ Sintered Composite Example IX	80 emu/g

Table 4: % Magnetoresistance $[100X(R_H - R_0)/R_0]$ at 5k and 290 K .

Product	% Negative MR at 5K	% Negative MR at 290 K
Example IV Sintered CrO_2	12%*	5%
Example V Sintered CrO_2	21%	2%
Example VI Sintered $\text{CrO}_2/\text{Cr}_2\text{O}_3$ composite	25%	33%
Example VII Cold Pressed $\text{CrO}_2/\text{Cr}_2\text{O}_3$ composite	21%	8%
Example VIII Sintered $\text{CrO}_2/\text{Cr}_2\text{O}_5$ composite	31%	22%
Example IX Sintered $\text{CrO}_2/\text{Cr}_2\text{O}_5$ composite	21%	8%

* 12% MR was found at 11K.

* MR in Example IV and VII was measured using Oxford high field magnet and cryostat Here H was parallel to the direction of current using standard four probe technique. MR in rest of the samples was measured using PPMS where H is perpendicular to the current direction.

Advantage of the present invention:

[00095] The present invention provides high purity chromium dioxide (CrO_2) having saturation magnetization of 132-135 emu/gm which is much higher than known samples of CrO_2 . Consequently, the pure CrO_2 of the present invention shows enhanced negative magnetoresistance at room temperature making it more useful as a magnetoresistive material in device applications.

[00096] The composites of the present invention exhibits enhanced negative magnetoresistance at low temperatures as well as near room temperature. They are obtainable in any ratio of their constituent compounds in sintered form. They are substantially homogenous. Because of their higher magnetoresistance near room temperature and substantial reproducibility, the composites of the present invention are very useful as magnetoresistive materials in device applications.

[00097] The process of present invention for manufacture of half metallic ferromagnet, high purity chromium dioxide (CrO_2), or composites of chromium dioxide and chromium sesquioxide ($\text{CrO}_2/\text{Cr}_2\text{O}_3$) or composites of chromium dioxide and Cr_2O_5 ($\text{CrO}_2/\text{Cr}_2\text{O}_5$),

- does not need high-pressure equipment, is simple to operate and is cost effective;

- gives a polycrystalline CrO_2 in bulk, having saturation magnetization value close to the theoretical value at a temperature of 5 K;
- gives the final product in desired shape of fairly good hardness, required for all practical purposes such as for measuring electrical resistivity and making magnetoresistive sensor etc.; This product which is fairly hard in the final form may be useful as target in Pulsed Laser Deposition and other techniques for thin film deposition.
- provides CrO_2 of substantially high purity suitable for spintronic devices.
- the % negative MR is found to be significant at room temperature depicting the spin polarization is maintained at such elevated temperatures, which is the consequence of very high purity sample.
- Provides composites in any desired ratio of the constituent compounds by a simple control of the temperature of heating the intermediate oxide.